Spar Technology as a Seabasing Enabler

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SUMMARY

A concept was developed by the Seabasing Innovation Cell within the Center for Innovation in Ship Design (CISD) at the Naval Surface Warfare Center Carderock Division (NSWCCD), West Bethesda, Maryland. The study was undertaken during February-May 2003 with funding provided by the Office of Naval Research (ONR). The concept was developed in Summer 2003 with further CISD funding and has been chosen for the 2004 Senior Year Design, Build and Test project by Florida Atlantic University's (FAU) Ocean Engineering Department.

The concept, known as the Deep Water Stable Craneship (DWSC) consists of two entities, a catamaran craneship and a detachable spar, which when connected form a self-deploying, open ocean capable trimaran. The spar can be rotated through 90 degrees, from horizontal to vertical, using seawater ballast. When vertical, partial de-ballasting 'lifts' the catamaran clear of the water surface allowing the system to operate as a spar and take advantage of the superior seakeeping afforded by the small waterplane area.

The concept was inspired by the 'ONR owned' and 'Scripts Institute operated' FLIPSHIP, and was developed as a potential solution to the Seabasing goal of transferring containerized cargo at sea between large and small vessels in seastate four (significant wave-heights 1.25-2.5m). Current crane operations at-sea are limited to seastate two (significant wave-heights 0.1-0.5m), largely due to pendulation of the load.

This paper presents the development of the concept, its performance in the areas of powering, stability, seakeeping, worldwide operability and alternative uses. In addition, the FAU 'demonstrator' is discussed as is a proposal for Flipship-II.

1. INTRODUCTION

The Center for Innovation in Ship Design (CISD) is a partnership, (signed 17-October-2002) between the Office of Naval Research (ONR) and the Naval Sea Systems Command (NAVSEA). Operating under joint-funding, and staffed by the ship design community of NAVSEA, the CISD functions as the Navy hub for supporting the National Naval Responsibility for Naval Engineering (NNRNE), a dedicated effort to ensure the sustained national capabilities to develop innovative designs for Navy ships and submarines. The CISD is an interdisciplinary activity devoted to the creation and development of breakthrough ship design technologies, ship concepts, processes and tools. The Center focuses on People, Knowledge and Innovation to nurture interest and develop experience in the field of naval engineering. The Center hosts Innovation Cells to investigate naval engineering topics of interest.

The CISD Seabasing Innovation Cell at NSWCCD focused on the *"Transfer of Materiel at Sea."* The Deep Water Stable Craneship concept (see Ref.1) was developed in response the seabasing goal of transferring twenty-foot Tonnage Equivalent Units (TEU) in seastate four *and* given the team's assessment of current operational limitations of ship-based cranes operating in a seaway.

This paper sets out to highlight the superior seakeeping of spar technology, and the potential utility within a Sea Base offered by a Deep Water Stable Craneship (DWSC). Following a brief overview of spar technology and FLIPSHIP, the focus turns to the development of the design and the performance of the DWSC in the areas of powering, stability, seakeeping, worldwide operability and alternative uses. An overview of the ~1:15 scale 'demonstrator' being developed by FAU and a FLIPSHIP-II is proposed.

2. BACKGROUND

An initial assessment of typical transfer mechanisms and materiel identified ship-based ramps and cranes as the most significant Sea Based enabling technologies, see Ref.[1]. Both however currently experience significant down-time as the prevailing seastate approaches significant waveheights[1] of approximately one meter (mid seastate 3). In the case of cranes this is due to relative motion, pendulation of the load and angular limits on the crane bearings. For ramps, relative motion is also key and leads to concerns about ramp hinge cracking due to torsional loading imposed by the relative motion. A potential solution to the ramp issue was developed (see Ref.1) but is not discussed here. For the crane problem, a solution was sought that enabled container transfer through seastate 4 (significant waveheights 1.25-2.5m), minimized pendulation of the load and would bridge the transfer problem between large and small vessels. The DWSC was the solution identified and subsequently developed.

3. SPAR TECHNOLOGY

3.1 OVERVIEW

The offshore world have developed and exploited a range of long cylindrical structures referred to as Spars. Common types of spar include the classic cylindrical spars, truss spars and cell spars, (see. Ref.[2] and Figure 1) all with length to diameter (L/D) ratios in the range 5-9 typically.

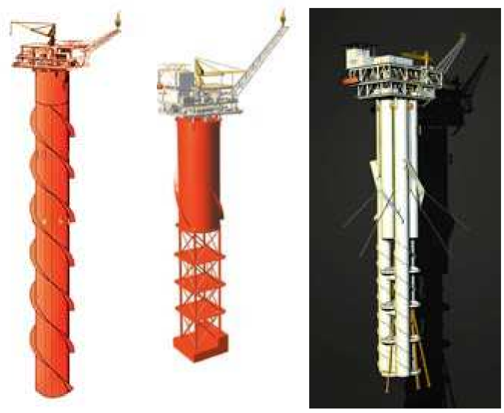


Figure 1 - Classic, Truss & Cell Spars

The classic cylindrical spar shown in figure 1 is fitted with 'spiraling strakes.' These inhibit the onset of vortex induced vibrations/motions that result from non-symmetrical eddy shedding. The Truss spar was developed to limit vertical motion of the spar – large flat plates improve heave damping. The open truss structure reduces size and cost. The third generation of spar, the cell spar, is an even more cost efficient design having smaller diameter sections (~20ft) enabling it to be built in the US using standard rolling technology.

The primary reason for the growth of spars is their inherent seakeeping performance. A strong contender in

[1] Significant Waveheight (Hs) : Average of the top one-third highest waves

the offshore world is the semi-submersible.

3.2 SPAR CHARACTERIZATION

A small selection of truss, cell and classic spar dimensions obtained via *Google*™ are plotted in figure 2 and show the variation in spar diameter and length to diameter (l/d) ratio. The DWSC and Flipship dimensions are also plotted for comparison. Of note, classic type spars tend to have much smaller diameters and larger L/D ratios than both cell and truss spars. It is pleasing to note that the DWSC characteristics fall 'neatly' on the trend between the cell spars and Flipship, suggesting the spar dimensions of the DWSC are viable.

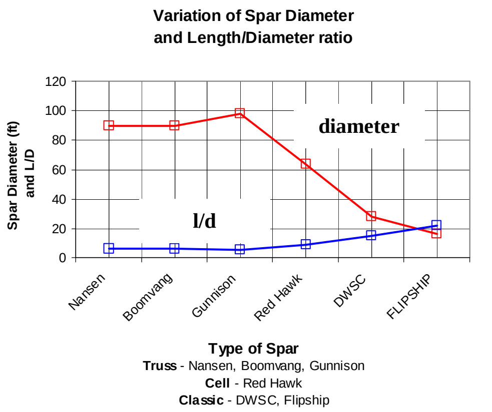


Figure 2. Typical spar diameters & L/D

The length to diameter (L/D) ratio for truss spars is typically ~6, rising to about 9 for cell spars. By contrast, Flipship has an L/D of ~22. Longer, more slender spars demonstrate less tendency to heave induced oscillation (resonance) given their smaller waterplane areas.

3.3 HEAVE MOTION

In terms of seakeeping performance the offshore community remain split between spars and semi-submersibles. Both have advocates who favor one over the other. One area of concern often raised in the context of spars is heave motion. The advocates of semi-submersibles are keen to point out that the large pontoons of such vessels, minimize any tendency to heave by their significant vertical damping. It is suggested here that a semi-submersible craneship would be less versatile in a seabasing environment and would be much less likely to be self-deployable over transoceanic distances than the DWSC.

For spars, the heave period is of the order of 20-30 seconds. This is such that heave resonance can occur in the presence of unusually large waves, when the modal period of such waves matches or is close to the natural heave period of the spar.

The natural heave period of Flipship is ~27seconds for the 600 tonne craft. This is approximately 3 times greater than the natural heave period for a Large Medium Speed Ro/Ro (LMSR) ship displacing ~64,000 tonnes (see Table 1).

Platform	Heave Period (secs)	Roll Period (secs)	Pitch Period (secs)	Displ't (tonnes)
Landing Craft Utility (LCU) 2000	5.0	6.3	4.4	1,087
Large Medium Speed Ro/Ro (LMSR)	8.4	20.4	8.2	63,978
Deep Water Stable Craneship	30.5	148.8	148.8	6,615
Flipship	27.0	42.0	42.0	600

Table 1. Natural Periods - summary

Indeed *Flipship,* (see figure 3. and ref. 4), a classic spar configuration, was 'excited' in heave during a particular storm.

Figure 3. Flipship during a 'flip'

During Flipship's heave excitation, tugs were called on standby but in the event were not required. The offshore industry has addressed this issue on spars with the use of heave-plates. They simply resist the tendency to heave and provide useful vertical plane damping.

It is worth noting the requirements for an offshore spar and those of a sea based spar craneship are different. The offshore spar's function is to enable well drilling; a function that places tight tolerances on the acceptable motions of the spar in much higher seastates than would be expected for a Sea Base. The current seabasing goal (ref.[5]) for transfer of TEUs[2] at sea is seastate 4 (significant wave-heights 1.25-2.5m) – contrast this with sustained operations through seastate 7 (significant wave-heights 6-9m) for offshore platforms.

4. DEEP WATER STABLE CRANE-SHIP (DWSC)

4.1 CONCEPT DESCRIPTION

The Deep Water Stable Craneship (DWSC) concept consists of two entities, a **catamaran craneship** (see Figure 4) and a **detachable spar** (see Figure 5), which when connected form a self-deploying, open ocean capable trimaran.

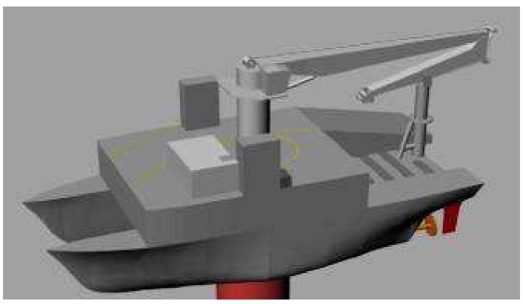


Figure 4. Catamaran Craneship

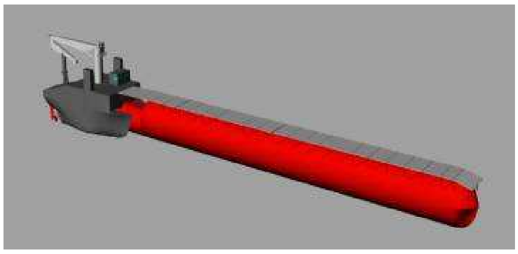


Figure 5. Catamaran and Spar

4.2 MODE OF OPERATION

The spar can be rotated through 90 degrees, from horizontal to vertical, using seawater ballast. Then, when vertical, partial de-ballasting 'lifts' the catamaran craneship clear of the water surface allowing the system to operate as a spar and take advantage of the superior seakeeping afforded by the small waterplane area. Returning to the horizontal from the vertical position, involves ballasting the spar to reduce its buoyancy and hence return the catamaran craneship to the free surface, then de-ballasting the spar in conjunction with some astern thrust of the catamaran will initiate the return to the surface of the spar. Figure 6. depicts graphically the various steps required in moving from the horizontal to the vertical and from the vertical to the horizontal. Table 2. describes the steps in their logical order.

[2] TEU : Twenty-foot Equivalent Unit

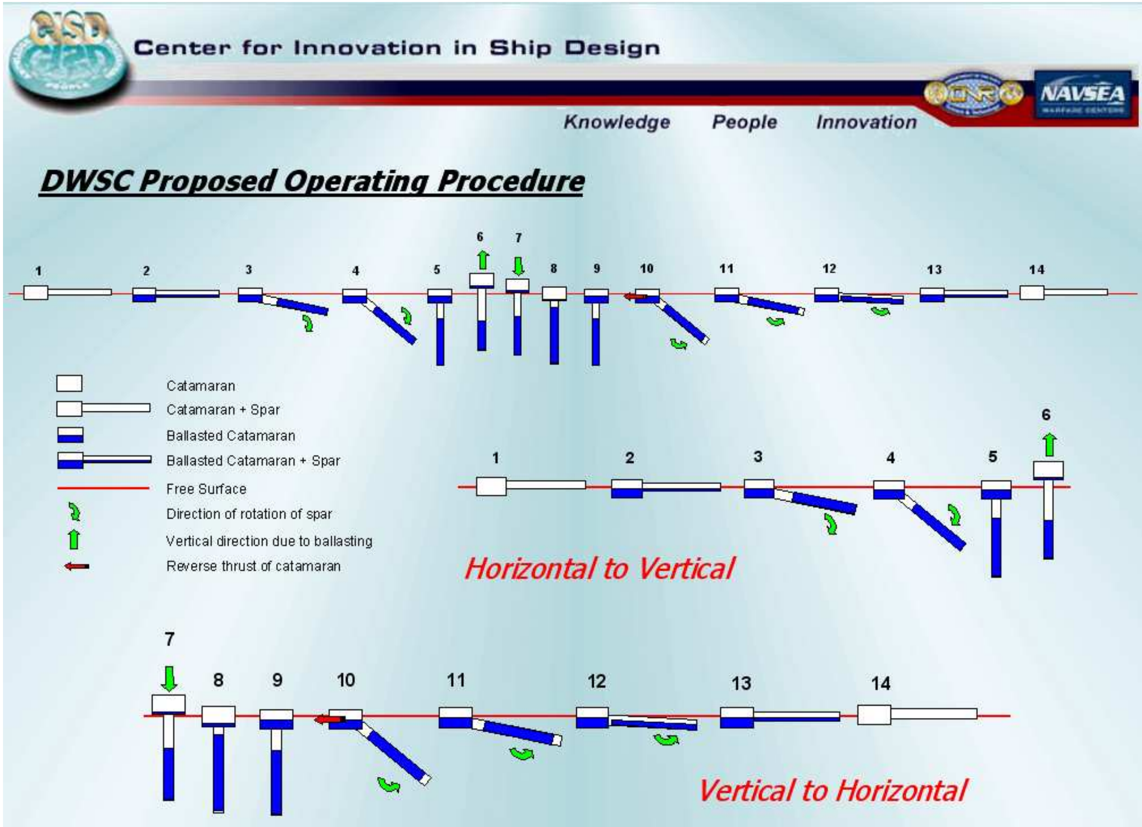


Figure 6. Ballasting Procedure

No.	CONDITION	STEP	COMMENTS
1	Surface	On surface	Normal operating draft and trim
2	Rotation prep	Achieve neutral buoyancy of Spar	Requires spar **and** catamaran to be ballasted/trimmed
2	Rotation prep	Release connectors	To allow spar to rotate
3 & 4	Rotation	Rotate spar to vertical	Shift spar ballast from aft to forward
5	Vertical prep	Attach connectors	To connect spar to catamaran
6	Vertical	Lift catamaran above surface	Blow ballast from catamaran **then** from high in spar
7 & 8	Vertical	Lower catamaran to surface	Add ballast low in spar
9	Rotation prep	Ballast catamaran to draft & trim appropriate for spar 'surfacing' or removal	Add ballast to catamaran **only** - ensure correct trim
9	Rotation prep	Release connectors	To allow spar to rotate
10	Rotation	Rotate spar to horizontal	Blow some ballast from low down in spar (or shift ballast from low down to higher up in the spar) and then drive catamaran in reverse to assist spar rotation
11	Rotation	Rotate spar to horizontal	As spar begins to rotate - stop astern revs
12	Rotation	Rotate spar to horizontal	During last few 'degrees' of rotation, move some spar ballast from forward to aft to correct the trim of the spar - if spar is still not vertical then slowly blow spar ballast until spar is horizontal.
13	Surface prep	Attach connectors	To connect spar to catamaran
13	Surface	On surface, achieve normal operating draft/trim	On the surface, de-ballast the spar and catamaran to achieve the normal operating draft & trim
14	Surface	On surface	Normal operating draft and trim

Table 2. Ballasting Narrative

5. CONCEPT DEVELOPMENT

5.1 INITIAL SIZING

The initial concept development focused on establishing a suitable design methodology that would result in a balanced design. Figure 7. shows the design methodology developed and adopted for the spar initial sizing.

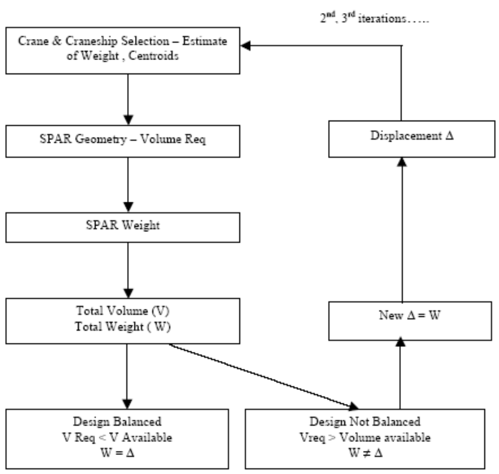


Figure 7. DWSC Design Methodology

Some initial design requirements were developed and assumed. The primary design requirement assumed was to limit the static heel angle of DWSC in vertical mode to less than 2.5 degrees with a 15 ton load at 30m reach. The 15 ton load was based on an 'average' load for a TEU. The 30m reach was chosen as it allowed for the half-breadth of the catamaran, a 'fender-offset' between the DWSC and a container ship, and enabled a TEU on the centerline of a Panamax containership to be picked up or set down. The 2.5 degrees of static heel was chosen from an understanding of ship-based crane bearings which are limited to roll angles of ~+/-5 degrees. So the combination of 2.5 degrees static heel and a 2.5 degree allowance for heel due to wave induced roll should ensure the crane is capable of operating at its maximum reach with a 15 ton TEU in a seaway. The seakeeping assessment would determine the wave induced roll angle.

Other unknowns included minimum clearance of the catamaran above the water in vertical mode, catamaran weight, spar weight, amount of ballast, sidehull separation, spar draft on the surface, resistance and powering etc. However, some initial engineering judgements and basic calculations allowed an initial design of the spar and the catamaran to emerge. These are shown in Figures 8 and 9.

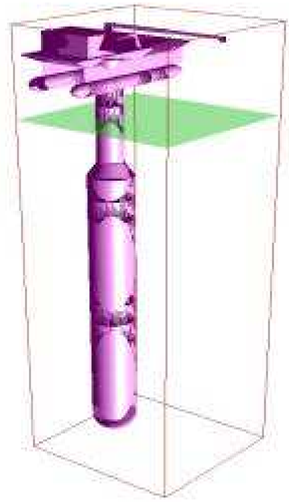


Figure 8. Initial DWSC in vertical mode

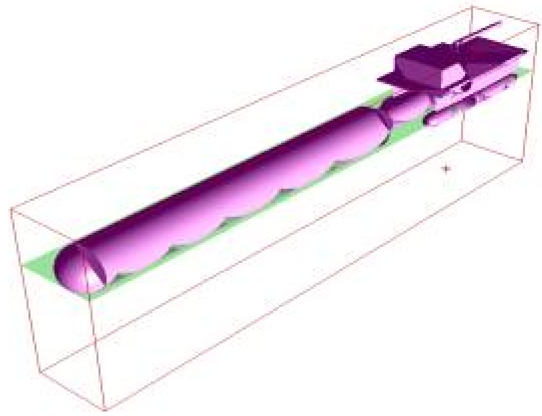


Figure 9. Initial DWSC in horizontal mode

The initial catamaran weight was assumed at 500 tons and the resulting initial spar design had an 11,000 ton displacement with 8,000 tons of seawater ballast. The initial reaction to this was that the spar was excessively large for the relatively light weight of the catamaran, and so a further effort was devoted to a more refined estimate of the DWSC.

5.2 DESIGN DEVELOPMENT

Having a better understanding of the design drivers, design methodology and sizing procedure, it was much easier to start to refine the design. Figure 10. shows the design spiral that was followed during the design development of a refined design effort.

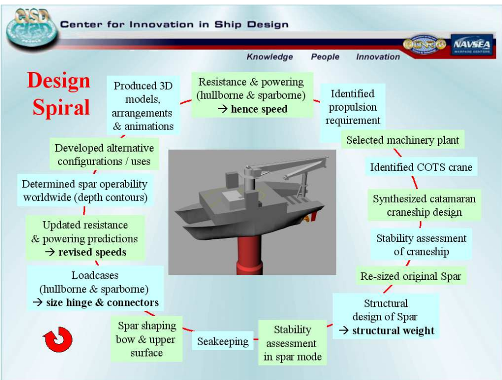


Figure 10. DWSC Design Spiral

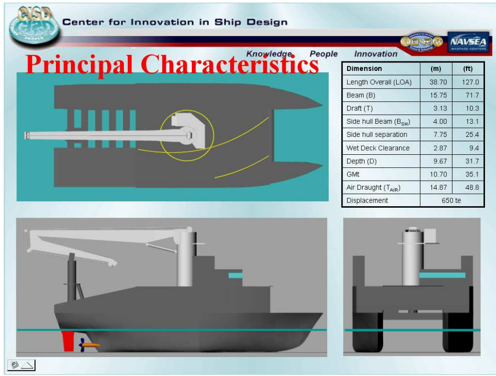
Aspects of the design that were addressed during the design spiral included; resistance and propulsion, selection of machinery and a Commercial Off-The Shelf (COTS) crane, design of the catamaran, stability, spar size and structural design, seakeeping, spar shaping, hinge and connector sizing, operability, alternative uses and for presentational purposes a short animation. This revised effort occurred over the summer of 2003.

The most fundamental conclusion from the initial sizing was that the spar size and design was dominated by the overall weight of the catamaran and so the first step to a more refined design was to develop a more robust weight estimate for the catamaran.

5.3 CATAMARAN DESIGN

Principal Characteristics

The catamaran principal characteristics are shown in Figure 11.



Dimension	(m)	(ft)
Length Overall (LOA)	38.70	127.0
Beam (B)	15.75	71.7
Draft (T)	3.13	10.3
Side hull Beam (B_{SH})	4.00	13.1
Side hull separation	7.75	25.4
Wet Deck Clearance	2.87	9.4
Depth (D)	9.67	31.7
GMt	10.70	35.1
Air Draught (T_{AIR})	14.87	48.8
Displacement	650 te	

Figure 11. Principal Characteristics

In summary, the overall length is 38.70m with a maximum beam of 15.75m and draft of 3.13m. The full load displacement of the catamaran is 650 tonnes and the installed power is ~4MW.

Hull Material

From the outset it was decided to adopt steel for the catamaran – despite being heavier than aluminum (which would help to reduce the size of the spar), it was anticipated that a steel catamaran craneship would be more robust in a seabasing environment.

The structural weight is a significant component of the overall weight. While USNS Hayes (see Figure 12.), is an oceanographic and towed array steel catamaran, it is significantly larger and heavier (~3,600 tonnes) than our intentions for the catamaran craneship.

Figure 12. USNS Hayes

A weight summary report for USNS Hayes was unavailable. Instead USNS Hayes was used for geometric scaling only i.e. overall size and dimensions.

Resistance & Powering

One of the major items of weight in the catamaran is the propulsion machinery. The initial design had raised some queries with respect to likely speed on the surface in 'trimaran' mode and speed when operating in vertical or spar mode. It was suggested a self deploying speed of ~20knots on the surface would ensure the DWSC could keep up with the fleet and arrive in theater in-time. In spar mode, a speed of ~3knots would provide the ability to resist currents, maintain station and to 'service' the length of a container ship during offload.

An initial estimate of surfaced resistance was based on scaling resistance data from a 27,000 ton high speed sealift trimaran design that had been tested at NSWC Carderock in 2002. The high speed sealift trimaran was particularly useful since it had similar slenderness (see Figure 13.) and was a source of valuable resistance test data.

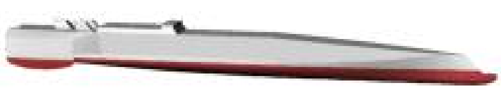


Figure 13. High Speed Sealift Trimaran

The DWSC surfaced displacement was estimated at ~2,200 tonnes. Table 4. shows the composition.

	Weight (tonnes)
Catamaran	650
Spar	1,220
Casing	100
Ballast Piping	50
Fuel	100
Margin	80
Surfaced Displ't	2,200

Table 4. DWSC Displacement Summary

The resistance data for the 27,000 tonne high speed sealift trimaran was scaled to 2,200 tonnes and plotted as a function of speed as shown in Figure 14.

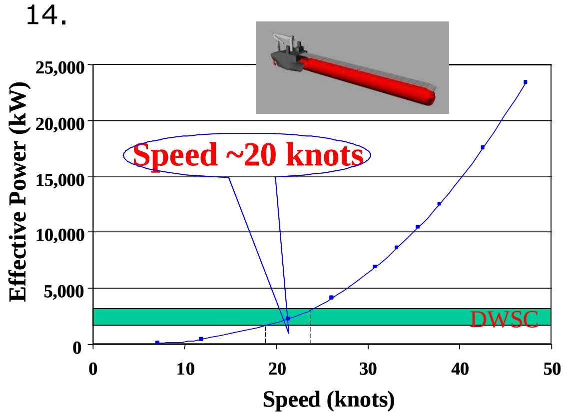


Figure 14. Power-speed plot (surfaced)

It can be noted from Figure 14., that a speed of ~20knots on the surface could be achieved with about 2.2MW of effective power. Assuming a propulsive coefficient (PC) of 0.6 requires about 3.7MW of power available for propulsion alone. Operating on the surface, the only other demand on the power supply will be hotel load, estimated for this vessel at ~0.3MW. This implies an installed power of about 4MW to achieve a surfaced speed of about 20 knots.

Powering requirements while in spar mode would have to contend with combined hotel load and crane usage, limiting the power available to propulsion. The crane electrical load was determined from the COTS crane selected. A Hydralift Offshore Knuckle Boom crane was chosen for its stowed compactness and its lift capabilities which ranged from 25 tons at 20m to 15 tons at 30m. The weight of crane and pedestal is 65.5 tonnes and it has a power requirement of 0.235MW. The COTS option, reduced the risk to the design and weight of catamaran as its characteristics were well known.

On application of an assumed PC of 0.5, the remaining power available to propulsion in spar mode is ~1.73MW, allowing for hotel load and crane use, or ~1.85MW allowing for hotel load only. This equates to a speed of ~4knots in spar mode, see Figure 15.

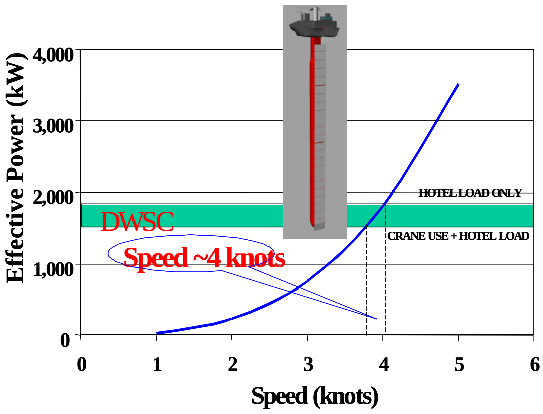


Figure 15. Power-speed plot (vertical)

The propulsors in spar mode are envisaged to be two pairs of tunnel thrusters arranged at 90 degrees to one another. The 90 degree 'separation' enables rotation via differential thrust.

A review of COTS tunnel thrusters identified thrusters that could deliver the required thrust and also could fit side by side in the diameter of the spar. Two pairs of 1,900hp thrusters will deliver enough thrust for ~3kts of speed in spar mode. So although there is sufficient propulsive power available for 4 knots, the available space in the spar dictates the use of smaller less capable thrusters that thereby limit the speed achievable in spar mode to ~3knots. This is considered acceptable to resist currents, or to move position when in spar mode.

Therefore, it was concluded that ~4MW of installed power would be sufficient for ~20knots surfaced and ~3knots in spar mode.

Propulsion Selection

Having identified the installed power requirement, the next step was to identify a propulsion plant capable of delivering that power. By coincidence, the UK Ministry of Defense's (MOD) trimaran research vessel RV Triton (see Figure 16.) has an integrated full electric power plant of 4MW.

Figure 16. RV Triton

The benefit of adopting the Triton plant was the availability of as-built and installed weights for the propulsion and electrical components – using this data would add further creditability to the catamaran weight by reducing the uncertainty associated with the propulsion and electrical machinery. Some adjustments to the weight data were necessary as Triton was a three hulled trimaran and we were designing a two hulled catamaran. For example, the cranehsip catamaran paid a weight penalty in some areas such as propulsion – Triton has one large motor and the catamaran craneship requires two motors (and a second gearbox) which are obviously heavier.

Catamaran Structural Weight

For structural weight, volumetric scaling of the merchant vessel MV Duplus, (see Figure 17.) a steel swath displacing 1,200 tonnes, was used to estimate the structural weight of the DWSC catamaran.

MV Duplus was a North Sea oil rig tender with a central drilling unit, and was later renamed MV Twindrill and modified from a SWATH to MWATH[3] which involved increasing the waterplane area of the struts to improve stability during crane operations. A weight summary was available for this vessel.

Figure 17. MV Duplus

Outfit

The outfit and furnishings were sized for an 11 man crew comprising 3 officers and 8 ratings. Weights for outfit and furnishings, auxiliaries and control and communications were scaled directly from RV Triton.

Armament

No armament fitted, other than a small firearms locker/magazine.

Variable Load

The bulk of the variable load was fuel at 50 tonnes for propulsion and electrical generation machinery. The remaining 16 tonnes of variable load comprised of water, lubricating oil, stores etc. Onboard fuel should be adequate for several days operation within a harbor.

For transoceanic crossings, it is proposed that the spar will be used to hold sufficient fuel for an un-refuelled transit. There is ample tankage volume in the spar to do so. Currently, some 400 tonnes of ballast water is required to ballast the spar (on the surface) to a suitable draft – fuel could be used in place of some or all of this seawater ballast.

Wet Deck Clearance

The Wet Deck Clearance (WDC) is the height of the catamaran cross-deck above the mean free surface and is normally 'set' with slamming and structural weight in mind. The higher it is the less likely slamming is to occur, but the heavier the structural weight will be. Given the design intent here is to minimize weight where practical to do so, identification of the minimum WDC was of interest. Reference to the US Navy's SWATH ship T-AGOS 19, which is designed to operate at all headings while towing arrays at the top end of seastate 6 ($H_{1/3}$ = 6m / 19.7ft), has wet deck clearances of 13ft bow, 9ft amidships and 11ft stern (3.96/2.74/3.35m) – larger at the bow and stern to avoid slams from pitching and from following seas. The wet deck clearance for the

[3] MWATH : medium waterplane area twin hull

craneship is slightly smaller at 2.87m given;

- Spar provides protection (when connected)
- No requirement to remain operational in higher seastates
- A high WDC aggravates structural weight & total displacement

So a compromise was required between structural weight, slamming and the ability to physically fit the spar under the wet deck when in surface mode.

Sidehull Separation

The sidehull separation of a catamaran is normally chosen based on stability – the wider the separation the better the stability, but again structural weight increases with increased sidehull separation. Here, the ability to fit the spar between the sidehulls also needed to be considered. Initially, the separation was set at 7m given the spar upper diameter of 6m (allowing 0.5m clearance on either side of the spar) and then stability was checked. The stability requirement was to limit the static heel during crane operations of a 15 ton lift at 30m reach to +/-2.5 degrees. The stability assessment concluded the need to increase the sidehull separation to 7.75m to meet the stability requirement. Sidehull separation affects structural weight and so the aim was to minimize the separation commensurate with achieving the stability requirements.

Catamaran stability can also be improved by increasing the beam of the sidehulls – however, stability varies as the square of the separation since catamaran sidehull separation is a more efficient manner of improving catamaran stability than increasing sidehull beam. The latter also affects powering more so than increasing sidehull separation.

General Arrangement

The desire to provide 360 degree unobstructed operation of the crane dictated the overall general arrangement of the catamaran. To minimize the impact on trim and/or heel of the catamaran, the crane was positioned on the centerline amidships. This position coincides with the 'seat' for the spar in vertical mode and so the spar seat and the crane foundation can be easily integrated. An alternative configuration (spar causeway, discussed in section 9.1) indicated the need for a 'driving lane and ramp' to be incorporated into the catamaran craneship design, and so a driving lane and stern slope were added on the starboard side, leaving the port side free for a small deckhouse.

Internally, accommodation is provided for 3 officers in single berths and 8 ratings in twin berths within the box structure. Other hotel service type spaces (e.g. galley, laundry, gym etc.) are also located there. Machinery is confined to the sidehulls and centered about amidships to limit the amount of 'correcting' ballast required to adjust the trim for spar 'lifting' operations. Power conversion equipment is located in the box structure. The cross-deck aft consists of box girders to 'tie' the sidehulls together – the deck area is not required and so the box girders offered a lighter weight alternative to fully plated in box structure aft. Fuel and other liquids are contained within tanks in the sidehulls – liquids are arguably the most efficient way to use the often 'difficult' space within sidehulls. Various anchoring positions were considered including under the cross deck forward, the sidehulls forward and the stern port quarter. The catamaran general arrangement is shown in Figure 18.

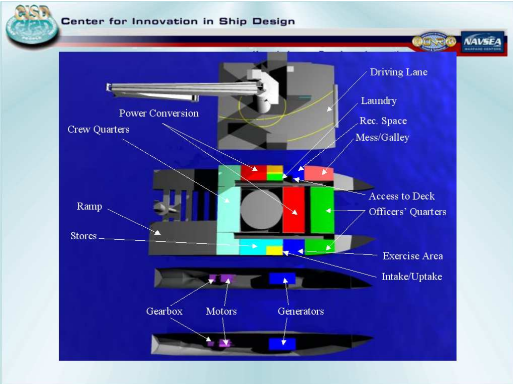
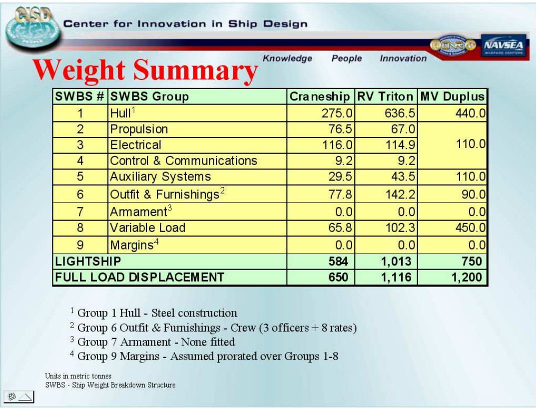


Figure 18. General Arrangement

Weight Summary

The US Navy's Ship Work Breakdown Structure (SWBS) was used to develop the weight estimate. This is shown in Table 5. For completeness and comparison, the SBWS weights for RV Triton and MV Duplus are also included.



Weight Summary

SWBS #	SWBS Group	Craneship	RV Triton	MV Duplus
1	Hull[1]	275.0	636.5	440.0
2	Propulsion	76.5	67.0	110.0
3	Electrical	116.0	114.9	
4	Control & Communications	9.2	9.2	
5	Auxiliary Systems	29.5	43.5	110.0
6	Outfit & Furnishings[2]	77.8	142.2	90.0
7	Armament[3]	0.0	0.0	0.0
8	Variable Load	65.8	102.3	450.0
9	Margins[4]	0.0	0.0	0.0
LIGHTSHIP		**584**	**1,013**	**750**
FULL LOAD DISPLACEMENT		**650**	**1,116**	**1,200**

[1] Group 1 Hull - Steel construction
[2] Group 6 Outfit & Furnishings - Crew (3 officers + 8 rates)
[3] Group 7 Armament - None fitted
[4] Group 9 Margins - Assumed prorated over Groups 1-8

Units in metric tonnes
SWBS - Ship Weight Breakdown Structure

Table 5. SWBS Weight Summary

It is worthy of note that both weight summaries available for RV Triton and MV Duplus did not specify the weight margins used, and so it was assumed that the margins were prorated over each of the SWBS groups. Consequently, no margin was specifically added to the catamaran craneship, to avoid applying 'margins-on-margins'.

6. SPAR DESIGN

6.1 SPAR DESIGN DRIVERS

The design drivers identified in the initial sizing and design of the spar were;

- Top weight
- Crane lift requirements
- Spar slenderness
- Structural integrity

Top Weight & Ballasting

Top weight, that is the overall weight of the catamaran, is significant because it has to be countered by ballast, which drives up the size of the spar. The options for countering top weight are permanent or fixed ballast e.g. lead, increased scantlings e.g. steel weight, and seawater ballast.

The fixed ballast option is attractive in spar mode due to the density of lead ~11 tonnes per meter cubed (t/m^3), compared with steel (~$7.8t/m^3$) and seawater ($1.0252t/m^3$), however fixed ballast is permanent and would exacerbate spar rotation, surfaced powering, connector and structural design and presents some through life maintenance issues.

The use of heavier scantlings was investigated and, while this may be attractive as a passive means of corrosion control, it does present some production problems and similar issues to the fixed ballast option. The density of steel is certainly attractive where weight/more robust structure is required.

By far the most effective solution is to use seawater ballast – it is readily available, provides for more flexible operations and fine control as the amount can be easily adjusted (by pumping and flooding) and it does not need to be carried all of the time – for surfaced transits, it can be easily pumped overboard. Seawater ballast was chosen for these reasons.

Crane Lift Requirements

The lift and reach requirements for the crane will result in a certain angle of heel for a given metacentric height, GM. The heel angle can be minimized by providing adequate GM. GM is determined by the amount and location of the seawater ballast and the size and shape of the spar, particularly in way of the waterplane.

Excessive GM will result in a larger than necessary spar, so the aim was to determine an acceptable level of GM commensurate with the lift requirements and an acceptable spar shape and size.

The GM determined/required was ~1.6m, and resulted from limiting the heel angle to less than 2.5 degrees with a 15 tonne load at 30m reach.

Spar Slenderness

The slenderness of the spar is determined by its length to depth (diameter) ratio (l/d). From a structural perspective the length to depth ratio is equal to l/d. For the GM selected, a long slender spar was required to provide the counterweight low down. The limit on length is imposed by the diameter, if the diameter is too small then a high l/d results and vice versa. Long slender structures (i.e. with high l/d ratios) can result in large bending stresses in the keel and upper deck in a seaway. Whipping is probably more significant and generally results in length to depth ratios of 15 maximum for standard ships. However, the US Navy have built and operated combatant ships with length to depth ratios greater than 15, for example DDG692 (15.44), DL1 (15.07), DLG9 (16.20) and CGN9 (15.33). Flipship has an L/D of 21.85 and has to survive as a ship when surfaced. The length to depth of the DWSC spar was limited to 15.0 as a reasonable compromise between slenderness, structural strength and the need to provide sufficient volume for seawater counter weight. In addition, it was necessary to assume a reasonable value of length to depth to allow the spar sizing process to start.

It is worth noting, the DWSC could be designed to a higher L/D than 15 as it does not have to maintain speed and/or heading in all sea-states in transit and is not expected to withstand shock loading, hence it could avoid conditions leading to whipping that surface ships face. The structural design is such that the pressure head calls for heavy gauge steel plating anyway and structural weight does not need to be minimized since the center of gravity (CoG) of the spar structure is below the CoG for the whole platform; therefore, thicker steel actually helps with stability, minimizes the amount of seawater ballast required and hence the size of the spar, and would enable a higher L/D to be achieved.

Structural Integrity

With a significant draft (~118m) the pressure head at the bottom of the spar is ~ 12bar, the tendency may be towards the need for submarine type structure. On closer examination, the bottom third of the spar does not need to be 'hard' as the pressure differential in this water filled section will always be very low; *the most efficient manner to rotate the spar is to flood the end (i.e. bottom) section first, so by the time the spar is in the vertical position, the differential pressure is very small*. Returning to the upright involves pumping some water out which will introduce a differential pressure (from 'out-to-in') and so a small hard tank may be required at the bottom of the spar to assist with the transition to the surface. The middle third will see higher differential pressures and so overall collapse and interframe collapse are of concern – just as with submarines, but traditional ship like scantlings should suffice, as the pressures are much smaller (~6bar at mid-draft). The upper third will require consideration of a 'hard tank' boundary, as the buoyancy of the whole system relies on the integrity of this boundary. Figure 19. shows the results of a basic parametric survey undertaken to determine the 'best' combination of spar length, diameter, and ballast.

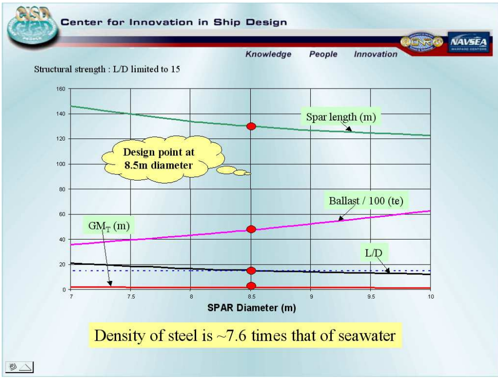


Figure 19. Spar Parametric Survey

The variation in ballast, length, L/D and GM were plotted against a range of spar diameters. The chosen L/D of 15 limited the range of diameters from 8.5 to 10m in this assessment. A spar diameter of 8.5m was selected as it minimized the amount of seawater ballast.

Of note, for a given L/D, increasing the spar diameter decreases spar length but drives up the seawater ballast requirement.

Example;

A diameter of 9.5m requires a length of 124.0m & 5,500te of ballast

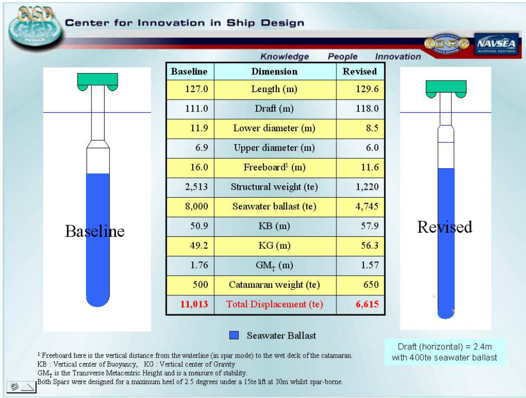
A diameter of 8.5m requires a length of 129.6m & 4,750te of ballast

So;

A 1m increase in diameter resulted in 6m reduction in length but a 750te increase in ballast. In addition, the respective densities of steel and seawater ensure that every tonne of steel removed in attempting to shorten the length pf the spar has to be replaced by 7.8 tonnes of seawater. So on this basis it is difficult to achieve significant reductions in spar length (draft). The spar proportions are driven by the top weight and the stability requirements in the vertical mode. Limits on L/D have been imposed to avoid structural issues while transiting in horizontal mode.

6.2 SPAR DIMENSIONS

Table 6. shows the principal characteristics of the initial and revised spar designs.



Baseline	Dimension	Revised
127.0	Length (m)	129.6
111.0	Draft (m)	118.0
11.9	Lower diameter (m)	8.5
6.9	Upper diameter (m)	6.0
16.0	Freeboard[1] (m)	11.6
2,513	Structural weight (te)	1,220
8,000	Seawater ballast (te)	4,745
50.9	KB (m)	57.9
49.2	KG (m)	56.3
1.76	GM_T (m)	1.57
500	Catamaran weight (te)	650
11,013	Total Displacement (te)	6,615

[1] Freeboard here is the vertical distance from the waterline (in spar mode) to the wet deck of the catamaran.
KB : Vertical center of Buoyancy, KG : Vertical center of Gravity
GM_T is the Transverse Metacentric Height and is a measure of stability.
Both Spars were designed for a maximum heel of 2.5 degrees under a 15te lift at 30m whilst spar-borne.

Table 6. Spar Principal Characteristics

The initial spar displaced ~11,000 tonnes. This seemed excessive for a 500 tonne top-weight. Closer examination of the design assumptions revealed a 16m freeboard i.e. the vertical distance from the mean free surface to the wet deck of the catamaran putting the keels of the catamaran at ~10m above the water – this equates to mid seastate 8 significant waveheights, and was considered excessive. The revised spar design reduced this clearance from 10m to 5.6m (high seastate 6) and in doing so reduced the displacement from ~11,000 tonnes to ~6,600 tonnes, a 40% reduction. Approximately 70% of this displaced volume is due to seawater ballast highlighting the importance of minimizing top weight and not imposing overly stringent stability requirements in the vertical mode.

In parallel, the catamaran was re-sized and its displacement grew from 500 tonnes to 650 tonnes. A spar displacing 6,600 tonnes was required to support the 650 tonnes catamaran.

7. PERFORMANCE

7.1 STABILITY

Stability was assessed periodically using Excel based calculations. As the design matured, a software tool called Paramarine (see Ref.6) was used to provide a more robust assessment of stability in the vertical condition. Time nor resources did not allow for fuller assessments of stability for each 'critical' stage in the operation and ballasting of the DWSC.

For the initial spar design, Paramarine estimated a +/-1.5 degree static heel with a 15 tonne load at 30m reach with 1.8m of GM. The stability requirement assumed was +/-2.5 degrees and so, in trying to minimize the size of the spar, for the revised spar design the GM was relaxed until the required heeling moment produced a +/-2.5 degree heel. The corresponding GM was ~1.6m.

7.2 SEAKEEPING

Effective seabasing is enabled by good seakeeping, and so it was necessary to quantify the seakeeping performance of the DWSC in spar mode. The proposed concept of operations for the DWSC in the Sea Base is to 'bridge the gap' between a large container ship and a small lighter such as an LCU 2000. Figure 20. shows the scenario that was modeled.

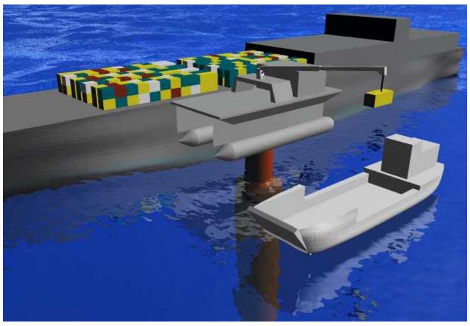


Figure 20. DWSC Seakeeping Scenario

NSWCCD seakeeping specialists were commissioned to undertake a seakeeping assessment of the three ship arrangement. The tool used was WAMIT (Wave Analysis by Massachusetts Institute of Technology) see Ref.7. WAMIT is particularly suited to the zero-speed, multi-body, in waves scenario of interest. WAMIT is a panel method, frequency domain ship motions program capable of modeling multiple independent floating bodies. Zero speed motions were calculated with six degrees of freedom for the DWSC, large medium speed Ro/Ro (LMSR) and an LCU 2000, at 15 degree headings, in seastates ranging from 2 through 6. Bretsneider Sea Spectra was adopted with modal periods of 8.8-20 seconds. The data was presented in terms of typical seakeeping polar plots.

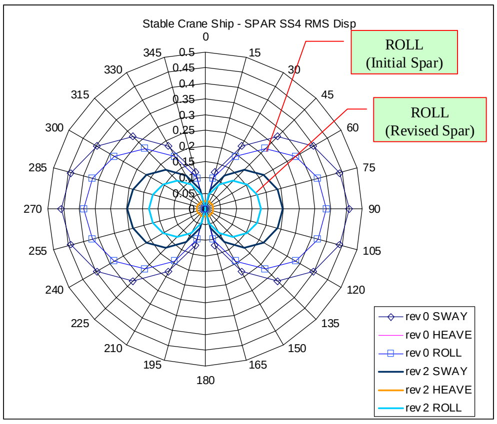


Figure 21. DWSC Seakeeping - SS4

Figures 21 and 22 show the results for the DWSC only in seastates 4 and 6 respectively for the initial and revised spars.

Assuming N=10,000 cycles, then the maximum values of heave, roll etc. can be estimated from 4.45 x RMS value (see Ref.8). Therefore, from Figure 21 it is noted that the maximum heave amplitude is ~0.11m in seastate 4. The maximum seaway induced roll angle is ~+/-0.8 degrees, therefore it can be stated that the maximum heel angle expected due to a 15 tonne lift at 30m in seastate 4 is ~+/-3.3 degrees for the DWSC. This is well within the current 5 degree limitation of current ship-based cranes being used by the US military. Figure 22. shows a similar plot for seastate 6.

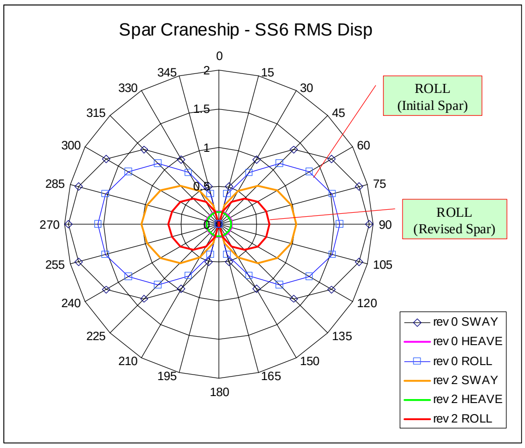
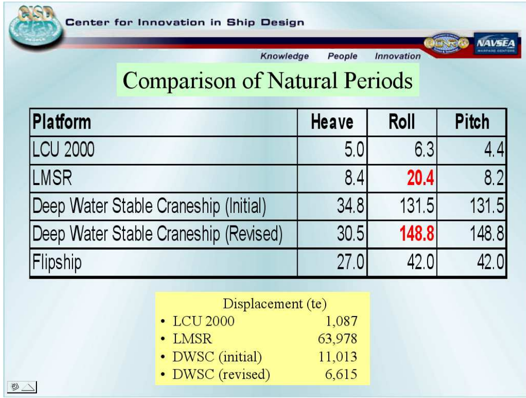


Figure 22. DWSC Seakeeping - SS6

The maximum heave amplitude is ~0.9m in seastate 6. The maximum seaway induced roll angle is ~+/-2.9 degrees, therefore it can be stated that the maximum heel angle expected due to a 15 tonne lift at 30m in seastate 6 is ~+/-5.4 degrees for the DWSC. This is exceptional performance compared to existing military craneships where 5 degrees will often be exceeded in seastate 2 or less, with much less demanding heeling moments. However, it is necessary to consider roll period as well as roll magnitude. Table 7. summarizes the natural periods for the various platforms considered.



Platform	Heave	Roll	Pitch
LCU 2000	5.0	6.3	4.4
LMSR	8.4	20.4	8.2
Deep Water Stable Craneship (Initial)	34.8	131.5	131.5
Deep Water Stable Craneship (Revised)	30.5	148.8	148.8
Flipship	27.0	42.0	42.0

Displacement (te)
- LCU 2000 1,087
- LMSR 63,978
- DWSC (initial) 11,013
- DWSC (revised) 6,615

Table 7. Comparison of Natural Periods

As can be noted from Table 7., the natural roll period for the LMSR is ~20 seconds, compared with a roll period of ~2.4 *minutes* for the revised DWSC. This suggests that pendulation of crane supported loads on the DWSC is not an issue. Combined with the small total roll angle (wave induced + static), the WAMIT assessment indicates a far superior level of seakeeping performance for crane based operations at sea, than currently exists. Moreover, this performance is achievable in a platform that displaces ~10% of the LMSR.

With a heave period higher than Flipship and a lower seastate operating requirement, it is unlikely that the DWSC would experience heave resonance hence the need for heave damping plates is not anticipated.

7.3 OPERABILITY

Given a draft of ~118m, concern was expressed about worldwide operability. The team met with the National Imagery and Mapping Agency (NIMA) who kindly provided their software, World Vector Shoreline Plus WVSPLUS®, which enabled the 200m contour to be plotted with ease. Ideally, a 130m contour would be more useful (given the 118m draft), however 200m represents the widely recognized 'boundary' between *shallow* and *deep* water. Figure 23. shows a sample of typical 'maps' produced.

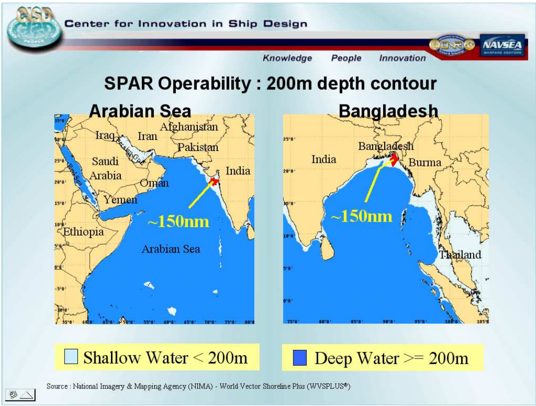


Figure 23. Spar Operability

The dark blue areas represent deep water (>200m) and the light blue areas represent the shallow water (<200m). WVSPLUS® also provides a useful distance function and so it is possible to determine the distance from the shore to the 200m contour at various locations around the world. The current thinking on Seabasing suggests a Sea Base could be up to 250nm offshore. The operability review confirmed there are very few places in the world where the water depth was less than 200m at a distance greater than 250nm from the shore. In addition, water depths some 60m shallower are likely to reduce the stand-off distance from the shore. It is suggested here the limiting factor for a Sea Base will be the stand off distance to ensure safety, particularly of commercial shipping re-supplying the Sea Base, rather than available water depth for spar operations.

8. HINGE & CONNECTORS

8.1 HINGE DESIGN

The design objective for the hinge was to provide an efficient means of afloat coupling and decoupling the spar (on the surface) to the catamaran. Horizontally and vertically, the structural connection between the spar and catamaran will be made by specially designed connectors, so the hinge should see no load in either configuration – instead, the purpose of the hinge is to act as a pivot point through which the spar will rotate during ballasting operations. The hinge will experience some reaction forces during rotation and rough order calculations estimated a 200mm diameter solid steel bar would be adequate.

To assist with the afloat coupling/de-coupling, a guide is required to ensure the hinge on the spar can self-locate prior to self-locking thereby minimizing any human intervention during potentially dangerous mating operations. Once in place, and prior to ballasting for rotation, manual connection of services is anticipated. Figure 24. shows an artists impression of the hinge and guides from a view between the sidehulls of the catamaran.

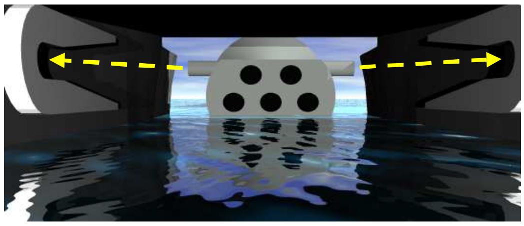


Figure 24. Hinge and Guides

8.2 CONNECTOR DESIGN

For extended operations on the surface and in spar mode, it will be necessary to firmly attach the spar to the cross deck of the catamaran via a number of connectors.

In spar mode, connectors will be fixed to the end of the spar and when operating in surface mode, the connectors will be on fixed on top of the spar. For both the spar-borne and surface borne modes of operation, various loadcases were identified as shown in Figure 25. and categorized as low, medium or high where low, medium or high represented the severity of the particular loadcase.

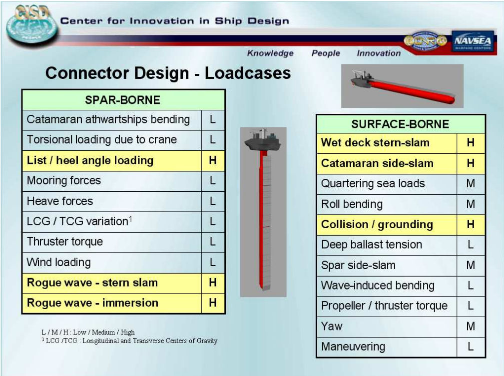


Figure 25. Connector Loadcases

Spar-borne Loadcases

Figure 26. shows the three loadcases assessed as *high* severity for spar-borne operations. The stern slam was estimated to be the most limiting loadcase of the three and so the end-connectors were sized to meet it.

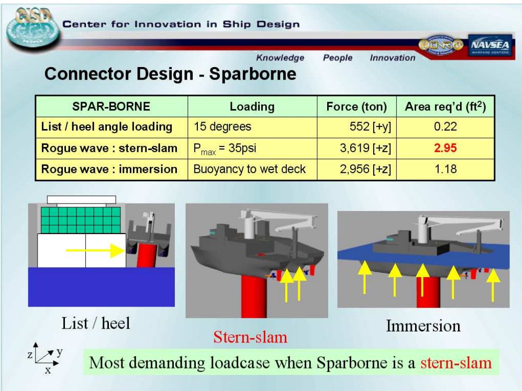


Figure 26. Spar-borne limiting loadcases

The cross-sectional area required for the spar-borne end-connectors was estimated at $0.27m^2$ ($\sim 2.95ft^2$).

Surface-borne Loadcases

Figure 27. shows two of the three loadcases assessed as *high* severity for surface-borne operations and Figure 28. shows the third. The catamaran side-slam was estimated to be the most limiting loadcase of the three and so the top-connectors the designed to meet it.

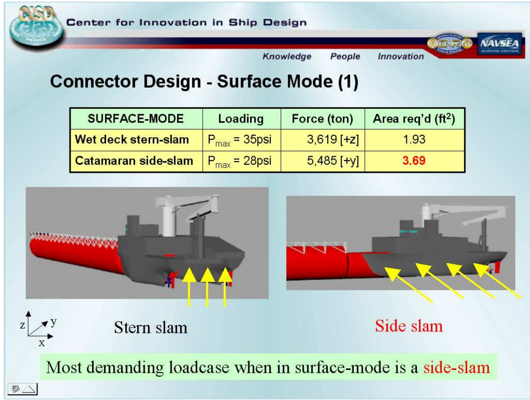


Figure 27. Spar-borne limiting loadcases (slams)

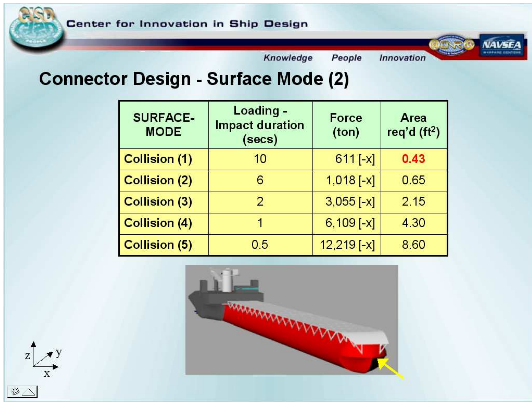


Figure 28. Spar-borne limiting loadcases (collision)

The cross-sectional area required for the surface-borne top-connectors was estimated at $0.34m^2$ ($\sim 3.69ft^2$).

Connector Sizing

Having identified the minimum cross sectional areas for the most severe loadcases in both the spar-borne and surface-borne modes of operation, the next step was to determine if there was sufficient area available on both the end and top surfaces of the spar to make the connections. Figure 29. shows the number of connectors required, their size and the assumed factor of safety used.

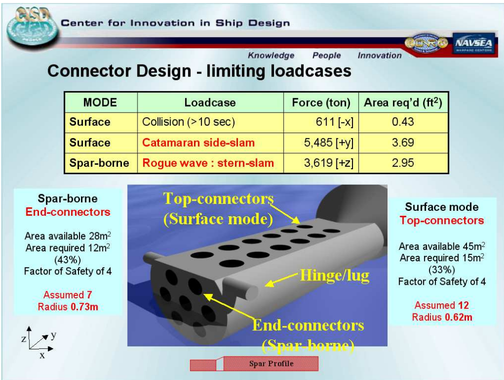


Figure 29. Connector Sizing

In spar-mode, ~40% of the available area would be required for connectors, assuming 7 in total with a factor of safety of 4. The resulting radius per connector was 0.73m.

In surface-mode, ~33% of the available area would be required for connectors, assuming 12 in total with a factor of safety of 4. The resulting radius per connector was 0.62m.

No effort has been given to the actual design configuration of the connectors – however, it is suggested that no new technology is necessary to implement suitable connectors for the DWSC application.

9. ALTERNATIVE USES AND CONFIGURATIONS

Figure 30. shows 5 possible configurations or uses of the DWSC.

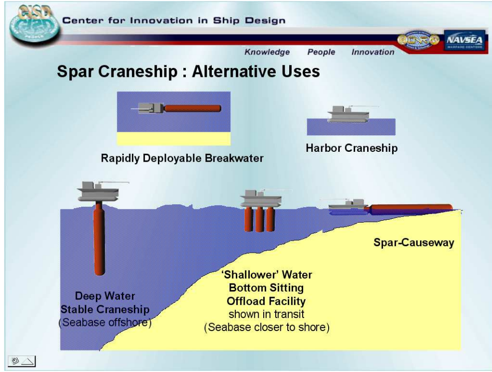


Figure 30. DWSC Alternative Uses

So far this paper has concentrated on the spar-mode of operation, with some attention to the utility of a small, container capable craneship in the littorals or in harbors. However, there are 3 other possible uses – each are discussed in turn.

9.1 SPAR CAUSEWAY

Since seakeeping is not concerned with the *shape* of the waterplane just its *size*, then altering the shape of the spar (for the same displacement) will have no affect on the seakeeping performance. One reason for wanting to change the shape from a cylindrical tube is to minimize the resistance on the surface when operating as a trimaran. A second reason may be so that the upper surface could become a driving lane (i.e. flat). The catamaran was designed with an offset driving lane, so that the spar could become a spar causeway (see Figure 31.) to enable troops and vehicles to leave a beach and board, for example, a high speed catamaran type vessel via the spar causeway.

9.2 SELF-DEPLOYING BREAKWATER

With an overall length of ~150m and an inherent ability to ballast down (even in surface mode), the DWSC can be used as breakwater, see Figure 31. Positioning the vessel parallel to shore would help to create a reasonable lee in which to conduct onload and offload operations in the surf-zone. Ballasting enables a deeper draft which will help to remove some of the energy from the longer period waves. In addition, this breakwater is self-deploying and can readily move where needed.

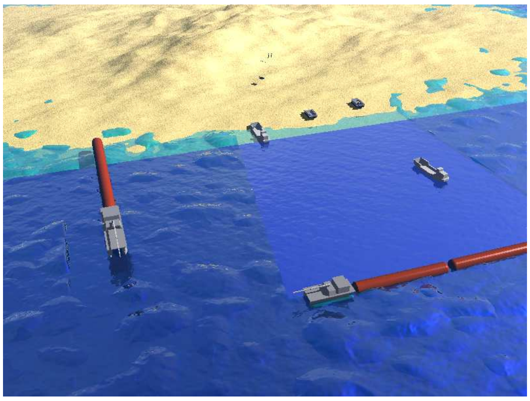
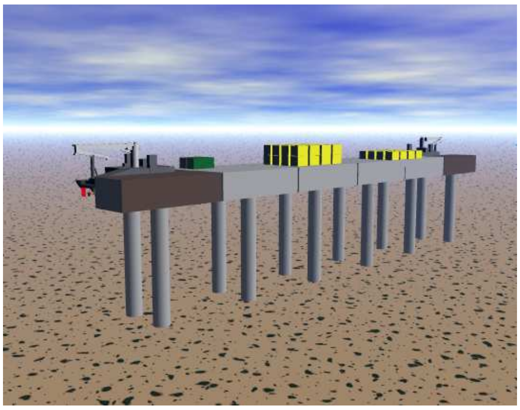


Figure 31. Spar Causeway & Breakwater

9.3 BOTTOM-SITTING OFFLOAD FACILITY

In recognition of the likely large number of containers required by a Sea Base, one option is the use of shorter-'stumpier' spars to provide a bottom-sitting offload facility in shallower water, see Figure 32. The concept of operations for such a facility would be as a 'seabased' storage facility where commercial containerships could moor to and offload their containers. Lighters would then come the facility for loading as and when required.



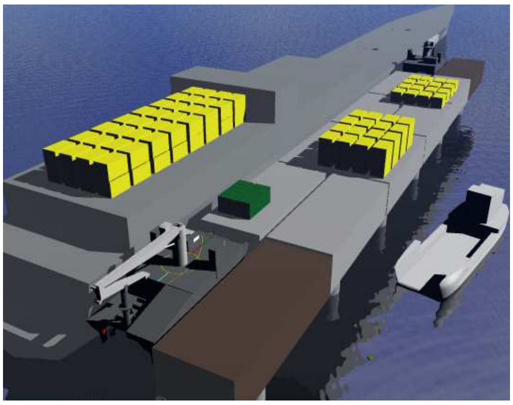


Figure 32. Bottom-sitting Offload Facility

9.4 LILY-PAD

It is reasonable to expect that alternative top-sides could be produced for different seabased functions. An example of this may be a flat-top for helicopter operations, providing a 'lily-pad' to extend the range of seabased helicopters.

10. FAU "DEMONSTRATOR"

10.1 BACKGROUND

With partial sponsorship from ONR, the Ocean Engineering Department of Florida Atlantic University (FAU) agreed to take the DWSC as the 2004/05 Senior Year Design, Build and Test project. NSWCCD/CISD are fulfilling the Project Advisor role and have provided a notional set of requirements for the 14-person team. In short, the FAU team are required to design, build and test in open ocean a ~1:15 scale spar craneship. While no working crane will be fitted, it is expected that a fully functioning ballast system will enable a spar to rotate, and lift a small catamaran clear of the free surface. Stability and motions will be recorded and performance on the surface as a trimaran will be observed. Work commenced September 2004 and will conclude with open ocean testing in mid-April 2005.

10.2 APPROACH

The team have divided into four sub-teams to develop in parallel the catamaran, the spar, the ballasting system, and the control and data acquisition system.

This project is developing and testing the students ability to design for simplicity and ease of construction, while reinforcing the importance of team working. Expected and actual performance will be quantified. The team are sub-contracting certain elements where they do not have the skills, nor equipment and so time, budget and risk management and planning are also key elements of the learning.

The sponsor stands to benefit from the detailed design perspective of the students, confirmation of the risk areas and from the performance data in a seaway.

11. FLIPSHIP-II

11.1 BACKGROUND

Flipship is a 42 year old vessel with significant maintenance requirements. A replacement design Flipship-II was proposed in the mid-80's. Flipship is largely a stable platform for sonar and oceanographic equipment/testing – her service life is being extended by acting as an R&D test platform for paying customers, but at some point, it will become unsafe to operate. Flipship is also costly to operate as *she* has to rely on large fleet tugs to be moved to and from designated operating locations.

11.2 PROPOSAL

One proposal may be to incorporate the sonar/oceanographic equipment and supports into a catamaran craneship (minus the crane), and use Flipship-II to not only provide / replace its current capability but also to test and de-risk the critical technologies (e.g. hinge, connectors, etc.) of a spar craneship – twice the value. In addition, Flipship-II would also provide self-deploying capability reducing the current reliance and through-life cost of fleet tugs for deployment. When Flipship capability is not required, the catamaran could work independently to support coastal and scientific studies.

12. CONCLUSIONS

Seabasing implies different meanings to different authorities; regardless of the Sea Base configuration, a current and future problem will be the transfer of materiel at sea. The current goal is to continue operations through sea-state four, see ref.5, where the maximum significant wave height is 2.5m.

The primary purpose of the Deep Water Stable Craneship is to provide a container transfer capability between large and small vessels, with sustained operations in higher seastates than is currently achievable today. However, as discussed, the DWSC can be easily reconfigured to meet a number of seabasing needs and is inherently a multi-purpose seabasing asset.

A perhaps less apparent conclusion is that a few DWSC dispersed throughout a seabase, would provide dedicated (and hence higher utilized) container transfer capability with significantly better performance than is currently achievable or likely to become achievable (without significant investment and time), for much less capital investment and through life cost. While this may be *transparent* now, the realities of conflict and logistics throughput from the sea will quickly highlight the existing deficiencies.

13. RECOMMENDATIONS

The integration of Flipship's role with that of a spar based craneship in the form of a Flipship-II would;

- maintain the capability provided by Flipship as a very stable test platform in support of sonar development and oceanographic research
- develop, de-risk, demonstrate and assist in transitioning the functionality and utility of a spar based craneship into the fleet for seabased logistics
- remove the reliance and cost of tugs/tenders, while providing a revenue earning capability in the form of a catamaran craneship in harbors or shallow water, during periods of low utilization

Further exploration of this concept to identify a notional set of requirements and a robust and costed concept design is recommended.

It is also recommended that suitable hinge and connector technology is identified; this may involve a new design or modification of off-the-shelf technology.

AUTHOR

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NOMENCLATURE

CISD – Center for Innovation In Ship Design
DWSC – Deep Water Stable Craneship
ESEM – Engineers & Scientists Exchange Memorandum
FAU – Florida Atlantic University
HSV – High Speed Vessel
LCU – Landing Craft Utility
LMSR – Large Medium Speed Ro-Ro
MV – Merchant Vessel
NNRNE - National Naval Responsibility for Naval Engineering
NAVSEA – Naval Sea Systems Command
NSWCCD – Naval Surface Warfare Center Carderock Division
NWDC – Naval Warfare Development Command
ONR – Office of Naval Research
WAMIT – Wave Analysis MIT

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